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Quarkonium production in pp collisions at 7 TeV

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Abstract

We present a selection of quarkonium production results obtained by the CMS experiment, on the basis of data collected in proton-proton collisions at a centre-of-mass energy of 7 TeV. The measurements include the production cross sections of prompt and non-prompt J/ψ mesons, as well as the fraction of J/ψ production due to b hadron decays, as a function of transverse momentum and in several rapidity ranges. The production cross sections of the Υ states are also presented, as well as their ratios, up to values of transverse momentum not previously explored.

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Quarkonium production in pp collisions at 7 TeV

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We present a selection of quarkonium production results obtained by the CMS experiment, on the basis of data collected in proton-proton collisions at a centre-of-mass energy of 7 TeV. The measurements include the production cross sections of prompt and non-prompt J/ψ mesons, as well as the fraction of J/ψ production due to b hadron decays, as a function of transverse momentum and in several rapidity ranges. The production cross sections of the $\Upsilon(nS)$ states are also presented, as well as their ratios, up to values of transverse momentum not previously explored.

Keywords: LHC, CMS, Quarkonium

1. The CMS detector and dimuon measurements

The heart of the Compact Muon Solenoid (CMS) detector [1] is a very large silicon tracker, consisting of pixel and microstrip detectors, immersed in a 3.8 T axial magnetic field, and extending over five units in rapidity. The high granularity of the tracker and the strong magnetic field ensure an excellent momentum resolution and good vertexing capabilities. Muons are measured in gas-ionization detectors embedded in the steel return yoke of the solenoid.

Figure 1: Opposite-sign dimuon mass distribution measured by CMS in pp collisions at $\sqrt{s} = 7$ TeV (left). Mid-rapidity dimuon mass distribution in the J/ψ (middle) and $Y(nS)$ (right) mass regions.

Figure 1 (left) shows the opposite-sign dimuon mass distribution reconstructed from the full 2010 data sample of pp collisions at $\sqrt{s} = 7$ TeV, of 40 pb^{-1} integrated luminosity. The J/ψ and $Y(nS)$ mass regions are shown in the other panels of this figure, for muons measured in the barrel detectors, where the dimuon mass resolution is around

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20 MeV/c² for the J/ψ and around 70 MeV/c² for the $\Upsilon(nS)$. The J/ψ and $\Upsilon(nS)$ results presented in this paper correspond to a relatively small fraction of the 2010 data, collected during the first months of LHC operation, when the instantaneous luminosity was low enough that CMS could write to permanent storage all the events with two muons, irrespectively of their charge or transverse momentum.

2. J/ψ production

On the basis of a dimuon event sample of 314 nb⁻¹ integrated luminosity, CMS measured the J/ψ production cross section in pp collisions at 7 TeV, as a function of transverse momentum and in three rapidity ranges: $|y| < 1.2$, $1.2 < |y| < 1.6$ and $1.6 < |y| < 2.4$ [2]. Figure 2-left shows the inclusive cross section, before separating the prompt and displaced J/ψ contributions. These two components can be discriminated thanks to the measurement of the distance between the dimuon vertex and the interaction point, known with a resolution around 50 μm . Figure 2-right shows the evolution of the fraction of J/ψ mesons resulting from b hadron decays with the J/ψ p_T . The strong increase with p_T is seen in all the three rapidity ranges probed so far by CMS. The pattern is very similar to the one previously observed by the CDF experiment, at lower energies [3], although we may be seeing that the values at the LHC energies are slightly higher.

Figure 2: Left: Differential *inclusive* J/ψ cross section, in the dimuon channel, as a function of p_T for three different rapidity intervals and in the unpolarized production scenario. The error bars represent statistical and systematic uncertainties added in quadrature. The global luminosity uncertainty (11%) is not added to each point. Right: Fraction of J/ψ production due to b hadron decays, vs. p_T , as measured by CMS and CDF.

Figure 3: Differential prompt J/ψ production cross section, as a function of p_T , for three rapidity intervals, as measured and as calculated using some models. The PYTHIA curve was used to calculate the abscissa values where the points are shown, following the procedure explained in Ref. [4].

The *prompt* component of the J/ψ differential cross section is shown in Fig. 3, as a function of p_T , for the three rapidity ranges mentioned above. The measurements are compared to calculations made with Monte Carlo event generators (PYTHIA and CASCADE), as well as with the Color Evaporation Model, as explained in detail in Ref. [2] and references therein.

Unpolarized quarkonium production has been used as the default scenario, by CMS as by the other LHC experiments, for the calculation of the dimuon acceptances for prompt production, given the rather puzzling situation regarding the available measurements at collider energies [5]. The theory calculations include an estimate of the contributions from the feed-down decays of heavier charmonium states ($\psi(2S)$ and χ_c), which should be responsible for more than 30% of the measured prompt yield [6]. It should be kept in mind that these contributions depend very significantly on the polarizations assumed for the different quarkonium states, which are essentially unknown at present. From the same *prompt* measurements, we can derive rather different *direct* J/ψ production cross sections, both in terms of yield and of shape of the p_T distribution, by simply changing the assumed polarization of the χ_{c1} and χ_{c2} states, and their relative yield as a function of p_T (see Ref. [7] for details). Important advances in our understanding of quarkonium production require, therefore, a robust experimental discrimination between the direct J/ψ component and the contributions from decays of other charmonium states, especially the 1P states. CMS has the potential to identify the radiative $\chi_c \rightarrow J/\psi \gamma$ decays (and the corresponding decays in the Υ family), either by using its calorimeters or by detecting the photon through its conversion to an e^+e^- pair in the silicon tracker. Despite the relatively low efficiency of the latter detection method, it remains the most suitable one for these rather low energy photons, especially because it should provide a mass resolution good enough to resolve the χ_{c1} and χ_{c2} states. Alternatively, we can perform a more direct study by measuring $\psi(2S)$ production, not affected by χ_c decays. Its yield is a factor 50 smaller than the J/ψ yield, in the dimuon decay channel, but analyses of $\psi(2S)$ and χ_c production should be feasible on the basis of the data sample collected by CMS in the year 2010 (around 2 million J/ψ dimuons).

Figure 4: Same as previous figure but for non-prompt J/ψ production.

The *non-prompt* component of the J/ψ differential cross section is shown in Fig. 4, together with some theory curves, calculated with the PYTHIA and CASCADE Monte Carlo generators as well as with the FONLL approach. A detailed description of the calculations is given in Ref. [2] and references therein. The CMS measurements are in very good agreement with the calculations.

3. Upsilon production

The CMS experiment has also measured the total and differential production cross sections of the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances, as a function of p_T , in pp collisions at 7 TeV, on the basis of a dimuon event sample of 3.1 pb^{-1} integrated luminosity [8]. The corresponding dimuon mass spectrum is shown in Fig. 5-left, for dimuons of p_T up to 30 GeV/c and in the full rapidity range. The CMS detector has a very good acceptance for $\Upsilon(nS)$ dimuons, down to zero p_T , as shown in Fig. 5-right.

A detailed description of the analysis, including an extensive report on the acceptance and efficiency corrections, and on the evaluation of all the systematic uncertainties, can be found in Ref. [8]. Here we only give a very brief

Figure 5: Dimuon mass distribution in the vicinity of the $\Upsilon(nS)$ resonances for $|\eta^\Upsilon| < 2$ (left), with the solid line representing the result of a fit to an underlying continuum component (dashed line) plus the three resonances. Acceptance as a function of p_T for dimuons from $\Upsilon(nS)$ decays (right), assuming unpolarized production.

summary. The $\Upsilon(nS)$ yields are extracted via an extended unbinned maximum likelihood fit. Each Υ state is parameterized by a “Crystal Ball” function, with the final state radiation tails fixed from Monte Carlo simulation studies and a single resolution parameter fitted from the data, constrained to scale with the $\Upsilon(nS)$ masses. The mass of the $\Upsilon(1S)$ is left free in the fit and the masses of the heavier states are fixed by their world average differences. A second-order polynomial is chosen to describe the background in the 8–14 GeV/c² mass range.

Figure 6: $\Upsilon(nS)$ differential cross section (left) and cross section ratios (right), as a function of p_T , in the rapidity range $|\eta| < 2$.

The p_T -differential $\Upsilon(nS)$ cross sections, for the rapidity interval $|\eta| < 2$, are shown in Fig. 6-left. The error bars represent the sum in quadrature of statistical and systematic uncertainties, excluding the global uncertainty on the luminosity (11%). The corresponding cross section ratios are shown in the right panel of the same figure. The luminosity uncertainty does not affect these ratios. The measurements clearly indicate that the relative cross sections of the 2S and 3S states, with respect to the 1S state, increase very fast with p_T , reaching a fourfold increase for the 3S state from $p_T \sim 2.5$ to $p_T \sim 25$ GeV/c. This increase can be attributed to several causes and only future measurements will allow for a clear understanding of the observation. For instance, part of this effect could be due to a steeper p_T dependence of the χ_b production cross section, leading to a more important feed-down contribution to the 1S state at low p_T than at high p_T , convoluted with the very reasonable assumption that the 1S state is much more affected by χ_b

decays than the heavier Υ states.

The $\Upsilon(nS)$ differential cross sections are compared in Fig. 7 with the PYTHIA expectation, normalized to the data so that differences in the shapes can be more easily appreciated. The data points are placed at abscissa values calculated using the PYTHIA curve, following the procedure described in Ref. [4].

Figure 7: $\Upsilon(nS)$ differential cross sections, as a function of p_T in the rapidity range $|y| < 2$, as measured by CMS and as calculated by PYTHIA. The calculation has been normalized to the measured p_T -integrated cross section.

Figure 8: $\Upsilon(nS)$ differential cross sections, as a function of p_T , as measured by CMS, D0 and CDF, normalized by the p_T -integrated cross sections.

To place the CMS measurements in a broader context, they are compared in Fig. 8 to previous results, published by the D0 [9] (only for the $\Upsilon(1S)$ state) and CDF [10] experiments. The measurements are normalized to the p_T -integrated cross sections to facilitate the comparison of the shapes. The CMS values correspond to the restricted rapidity interval $|y| < 1$, an intermediate case between the ranges covered by CDF, $|y| < 0.4$, and D0, $|y| < 1.8$.

For completeness, Fig. 9 shows the measured dimuon mass distributions, before accounting for acceptance and efficiencies, in the fifteen p_T intervals used for the $\Upsilon(1S)$ differential cross section measurement.

Once CMS will finish the analysis of the full 2010 data sample, of 40 pb^{-1} integrated luminosity, we will be able to make a more informative study of the high- p_T region, including detailed comparisons to theory calculations. It will also be possible to perform a simultaneous measurement of the polarization and production cross section, as a function of p_T . The importance of having a reliable understanding of the polarization is illustrated in Fig. 10, which shows the measured $\Upsilon(1S)$ differential cross section, as a function of p_T , with acceptance corrections calculated assuming two extreme polarization scenarios: fully transverse ($\lambda_\theta = +1$) or longitudinal ($\lambda_\theta = -1$) polarizations, in the helicity frame. It should be noted that the polarization is expected to change with p_T , so that reality might be, for instance, similar to the $\lambda_\theta = -1$ data points at low p_T and similar to the $\lambda_\theta = +1$ data points at high p_T .

Figure 9: Dimuon mass distributions in the specified p_T regions, for $|\eta^{\mu\mu}| < 2$, before accounting for acceptance and efficiency.

Figure 10: $\Upsilon(1S)$ differential cross section, as a function of p_T in the rapidity range $|y^T| < 2$, as measured by CMS, with acceptance corrections calculated in two extreme polarization scenarios.

4. Summary

After only a few months of data taking, the CMS experiment is operating extremely well and producing high-quality physics results, as illustrated by the selection presented in this article. Complementing the measurements of (relative) production cross sections of several quarkonium states with the measurement of their polarizations, CMS will surely contribute to a significant improvement in our understanding of quarkonium production.

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